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"The Development and Prevention of Channel Segregation during Alloy Solidification

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This research began on the simple premise that since channel segregation is a consequence of natural convection ("thermo-solutal" or "thermo-haline") suitable mold movement during the course of alloy solidification should prevent or reduce the incidence of well-defined channels ("A" segregation or "freckles"). The P.I. frequently suggested this to John Hunt during the latter's pioneering research in the late 1960s, but it was not taken up at that time. After a decent period of some 10 years (1970-1980) it seemed more than timely to pursue the matter further.

The work began with Alex Sample as an undergraduate assistant in 1981, continued as he progressed to an MS graduate student (1982-1984), followed, over the years, by Joe Sarazin (1984-1990), Jinsung Jang (1987-1990), and Scott Steube (1990-), with a contribution from a visiting scholar, Fang Dacheng (1985-1987). Numerous undergraduates contributed during summer periods. Joe Sarazin and Scott Steube also entered the program in this way.

The initial idea proved to be correct, it being demonstrated that with a slow (< 10 rpm) precession about an inclined axis (≈ 30° to vertical) base chilled castings of the transparent NH_4Cl-H_2O analogue solidify without the usual chemical segregation (Ref. 1). It was subsequently shown that the same was true of metal ingots, using the Pb-Sn system (Refs. 2 and 3) and, indeed, that here was simple method of preventing channel or freckle formation (Ref. 4).

While the original idea worked in practice, the actual mechanism by which it operated was less obvious. At that time, it was supposed that channels developed within the mushy region of a casting and somehow found their way to the growth front, emitting plumes of solute rich liquid. Analyses purporting to explain how this happened were propounded by Flemings, Moore, Beech, and coworkers. But, one does not drain a swamp by digging ditches in the middle, rather by making an opening or breach at the edge -- i.e., at the growth front -- from which liquid can escape. It was shown that this was the case by starting channels with induced plume flow above the channel mouths, but fall and collect within the channel to form a local equiaxed debris. This explains the polycrystalline structure of freckles which are to be seen on directionally grown alloy specimens. See Refs. 14 and 18.

Observation of these convection patterns continually emphasized the importance of plume flow in transporting ripened dendritic fragments into the bulk liquid, where they become potential equi-axed grains. In this connection, it was instructive to use the aqueous NH_4Cl system to study grain formation in long, inclined molds, with side chill, thereby stimulating the geometry of a steel continuous caster. Using this arrangement and making careful extrapolation of physical properties and thermal conditions to steel, it was possible to predict equiaxed grain sizes in continuously cast steel strands which agreed very closely with observation (Refs. 15 and 16). Further studies of grain structure in continuous steel castings have continued, in conjunction with the Inland and U.S. Steel Companies. This is heavy work, but something will be published in due course.

Following this, it seemed promising to see if it would be possible to correlate dendrite ripening and fragmentation with transport of such crystal fragments into open liquid by convection, and to follow their survival and growth to produce equiaxed grains, subsequently to cause the columnar/equiaxed grain transition. This would provide a physically realistic alternative (Ref. 17) to current models which describe equiaxed formation on a basis of heterogeneous nucleation on unidentified substrates (Oldfield, Stefanaseu, Dantzig, Rappaz, and others). This is the current preoccupation, with continuing support from NASA (NAG-3-1462) and from the NSF.

All of this seems to have taken a long time (12-13 years!) and to have used up a significant sum of money. Even so, it has to be said, that we still are not yet able to predict, specifically, numerically, whether or not there will occur channel segregation in a given situation. That is a rather lame admission. Part of the problem is connected with the mathematics of handling the perturbation analysis which relates the dendritic boundary layer at the growth front to the bulk open liquid, and, simultaneously, to the trapped interdendritic liquid. The probable wave length of such a perturbation is now thought to be close to that of the primary dendritic spacing ($\approx D/V$), as was suggested in Refs. 3, 10, and 14, but the permeability and depth of the mushy region are complicating factors which are not fully understood: Poirier is concentrating on the latter.

What could be claimed from the program, here, at Michigan Tech, is that we have shown the following:

1. Suitable, slow precessional movement of a mold, during solidification, causes the partly solid material to translate with respect to the open liquid (the latter is stationary) in such a way as to inhibit channel formation.

2. Channels originate by a perturbation in the bulk liquid, close to the dendritic growth front and develop backwards into the mushy region like a drainage channel. Mold movement disturbs this convection by sweeping the bulk liquid across the front (actually the reverse), rather as a cross wind prevents smoke from coming out of chimney.

3. With sufficient solutal buoyancy, channel/plumes occur in all alloy systems where a dendritic mushy region develops, although molten ionic salt systems have proved obstinate. The dimensions of the channels are remarkably similar across three orders of Prandtl number.

4. Measured flow rates for aqueous and organic materials have been analyzed and are compatible, so that extrapolation of the model analysis to opaque metals seems to be justified, predicting channel flow rates in the latter of around 10 cms/s.

5. The polycrystalline structure of freckles in superalloys, or similar, is explicable in terms of the settling of ripened dendritic fragments within open channels in the dendritic mushy region.

6. The importance of channel/plume flow as a transport mechanism for crystal fragments has been emphasized, and may lead to a more physically realistic model to predict the grain structure of castings.

NAG - 3 - 560 - REFERENCES 1 - 18

1. "The Effect of Mold Precession on Channel and Macro-segregation in Ammonium Chloride-Water Analog Castings," A.K. Sample and A. Hellawell, Trans. Met. Soc. AIME, 13B, 495-501 (1982).

2. "The Use of Analogue Casting to Study Channel Segregation," A. K. Sample and A. Hellawell, in Modeling of Casting and Welding Processes II, Met. Soc. AIME, Proceedings, 119-125 (1983).

3. "The Mechanisms of Formation and Prevention of Channel Segregation during Alloy Solidification," A. K. Sample and A. Hellawell, Trans. Met. Soc., AIME, 15A, 2163-2173 (1984).

4. "Method for Reducing Macrosegregation in Alloys," A. Hellawell, U.S. Patent #4,462,454 (July 31, 1984).

5. "Mechanisms of Formation and Prevention of Channel Segregation during Alloy Solidification," A. Hellawell, in Solidification and Fluid Dynamics in the Earth's and Space laboratory, Giesserei Institut, RWTH, Aachen, 197-223 (March 1984).

6. "Channel Segregation in Alloy Ingots," A. Hellawell, Proceedings of International Steel Foundry Congress, Chicago, 295-306 (Nov 1985).

7. "Local Convective Flows in Partly Solidified Alloys," A. Hellawell, in Structure and Dynamics of Partially Solidified Systems, Ed. D. Loper, NATO-ASI Series E, #125, 5-22 (1987).

8. "The Surface Morphology of Crystals Melting under Solutions of Different Densities," Fang Dacheng and A. Hellawell, J. Crystal Growth, 92, 364-370 (1988).

9. "Channel Flow in Partly Solidified Systems," J. R. Sarazin and A. Hellawell, in Solidification Processing 1987, The Institute of Metals, London, Book #421, 94-97 (1988).

10. "Channel Formation in Pb-Sn, Pb-Sb, and Pb-Sn-Sb Alloy Ingots and Comparison with the System NH_4Cl-H_2O," J. R. Sarazin and A. Hellawell, Met. Trans. AIME, 19A, 1861-1871 (1988)

11. "Macro- and Micro-Segregation during Alloy Solidification," A. Hellawell, in F.

Weinberg International Symposium on Solidification Processing, Eds Lait and Samerasekera, Pergamon Press, 395-411 (1990).

12. "Segregation Arising from Natural Convection during Solidification," J. R. Sarazin and A. Hellawell, E.P. D. Congress 91, Ed. Gaskell, The Minerals, Metals and Materials Soc., 511-522 (1991).

13. "Studies of Channel-Plume Convection," J. R. Sarazin, R. S. Steube, and A. Hellawell, in Nature and Properties of Semi-Solid Materials, Eds. Sekhar and Dantzig, The Minerals, Metals and Materials Soc., 143-152 (1992).

14. "Channel Convection in Partly Solidified Systems," A. Hellawell, J. R. Sarazin and R. S. Steube, Phil. Trans. Roy. Soc., London, 345, 507-544 (1993).

15. "The Use of NH_4Cl-H_2O Analogue Castings to Model Aspects of Continuous Casting," J. Jang and A. Hellawell, J. Ironmaking and Steelmaking 18(4), Part I - "Asymmetry in Inclined Moulds," 267-274 (1991).

16. -- ibid., Part II - "Columnar-Equiaxed Grain Transition and Crystal Sedimentation Rates," 18(4), 275-283 (1991).

17. "An Alternative Approach to Modeling the Grain Structure of Castings," R. S. Steube and A. Hellawell, American Soc. Mech. Engrs, Heat Transfer Division - 218, 73-83 (Book #G00704 - 1992).

18. "The Use of a Transparent Aqueous Analogue to Demonstrate the Development of Segregation Channels during Alloy Solidification Vertically Upwards," R. S. Steube and A. Hellawell, Int. Video-Journal of Engr. Research -- in press, imminent -- Technical Officer, T. Glasgow, has a copy of the accompanying video tape.